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QUARK-NOVAE, COSMIC REIONIZATION, AND EARLY R-PROCESS ELEMENT PRODUCTION

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ABSTRACT

We examine the case for Quark-Novae (QNe) as possible sources for the reionization and early metal enrichment of the universe. Quark-Novae are predicted to arise from the explosive collapse (and conversion) of sufficiently massive neutron stars into quark stars. A Quark-Nova (QN) can occur over a range of time scales following the supernova event. For QNe that arise days to weeks after the supernovae, we show that dual-shock that arises as the QN ejecta encounter the supernova ejecta can produce enough photons to reionize hydrogen in most of the Inter-Galactic medium (IGM) by $z \sim 6$. Such events can explain the large optical depth $\tau_e \sim 0.1$ as measured by WMAP, if the clumping factor, C, of the material being ionized is smaller than 10. We suggest a way in which a normal initial mass function (IMF) for the oldest stars can be reconciled with a large optical depth as well as the mean metallicity of the early IGM post reionization. We find that QN also make a contribution to r-process element abundances for atomic numbers $A \geq 130$. We predict that the main cosmological signatures of Quark-Novae are the gamma-ray bursts that announce their birth. These will be clustered at redshifts in the range $z \sim$ 7-8 in our model.

Subject headings: Reionization – Quark-Nova – r-process – Gamma-Ray bursts

1. INTRODUCTION

The end of the cosmic “dark age” began with the production of reionizing UV radiation from the first luminous objects. Several independent lines of evidence, including recent WMAP results suggest that beginning at redshifts of about $z \sim 17$, an inhomogenous and possibly non-monotonic decrease in the fraction of neutral H and He in the IGM took place, and that this process was largely completed by $z \sim 6$. The nature of the first ionizing sources is still mysterious - possible candidates for “early” sources (i.e., well before $z \sim 6$), include metal-free Population III (Pop III) stars, high-z dwarf galaxies, intermediate-mass black holes or sterile neutrinos. Current models favour luminous objects that formed from collapsed gas haloes of mass $M \sim 10^6 M_\odot$.

Although quasars and active galactic nuclei (AGNs) are efficient emitters of UV photons, results from the Sloan Digital Sky Survey (SDSS) imply that they contribute much less to the ionizing radiation than star-forming galaxies at high redshift (Fan et al. 2006). The first stars, owing to their metal-free composition (Z=0) which makes them a copious source of ionizing photons, are increasingly viewed as prime candidates for early reionization sources. It has been argued that a top-heavy IMF (40-100$M_\odot$) may be required to explain the large WMAP optical depth and the ongoing overlap of HII regions at lower redshifts $z \lesssim 9$ suggested by IGM temperatures inferred from the Lyα forest (Theuns et al. 2002). Pop III stars derived from a top-heavy IMF can emit as many as 10^5 ionizing photons per baryon during the star's life (Tumlinson&Shull 2000; Bromm et al. 2001; Schaerer 2002). A population of very massive stars (VMS), that have been linked to pair-instability SNe, was advocated by Qian & Wasserburg (2002) to explain r-process element abundances as well as that of C, O and Si in some extremely metal-poor stars, while other works (Tumlinson et al. 2004; Daigne et al. 2004; Venkatesan & Truran 2003; Fang&Cen 2004) argue that an ordinary Type II-SN IMF can explain these abundances just as well while also providing the large optical depth τ_e measured by WMAP. Furthermore, the escape efficiency of UV photons required for early reionization is smaller for a top-heavy IMF than for the VMS, making the former better candidates for reionization sources.

While the high production of ionizing photons from a top-heavy Z=0 stellar population is desirable, their short lifetimes (few million years in the absence of significant mass loss) imply that successive generations do not remain metal-free. This creates some major difficulties. The issue here is that the IGM is rapidly polluted in metals [4]. This “negative feedback” mechanism (e.g. Sokasian et al. 2004; Ricotti & Ostriker 2004) is a problem - it might result in the reneutralization of the IGM, calling for another sub-epoch of reionization from a different stellar population in a metal-enriched IGM. This may necessitate double or even multiple reionization (Wyithe & Loeb 2003). It may be possible to extend the Pop III lifetime by “hiding” most heavy elements in the collapse to black holes, with added benefits of ad-

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[4] Analysis of quasar metal absorption lines have shown that the IGM is enriched in heavy elements from a level of $\sim 10^{-4}$ $Z_\odot$ at $z \sim 5.3$ to $\sim 10^{-3}$ $Z_\odot$ at $z \leq 4.3$ where $Z_\odot$ is the solar metallicity (Songaila 2001). That such an abundance of heavy elements is observed commonly and uniformly in the low-density IGM where no bright galaxies are found may be due to outflows from small protogalaxies (Madau et al. 2001; Mori et al. 2002), but prompt enrichment by Pop III stars provides a more natural solution for the distribution of metagalactic heavy elements.

ditional accretion generated X-ray photons, but this appears to require extreme black hole formation rates and smaller than normal metal yields from Pop II stars (see Ricotti&Ostriker 2004 for a discussion).

In this paper, we argue that explosions that result from the conversion of neutron stars (born from progenitors with mass in the $25M_\odot \leq M \leq 40M_\odot$ range) to quark stars - known as Quark-Novae (QNe; Ouyed et al. 2002) - may be important sources of reionizing UV photons. This mechanism has the advantage of not leading to heavy chemical pollution of the IGM or ISM, thereby alleviating the requirement of producing several generations of chemically pristine massive stars early on in cosmic star formation history. The first QNe in the universe can occur very soon after Pop III stars end their lives as Supernovae (SN) - in fact the time delay between the SN and the subsequent QN is one of the main parameters of QN theory (Ouyed et al. 2007). The ioinizing photons are produced when QN shock waves overtake their progenitor SN shocks (Leahy&Ouyed 2008). Copious energy releases can occur in this way if the QN delay is days to months after the initial SN. QNe can provide enough UV photons to explain the large optical depth measured by WMAP. The contribution to reionization from the main-sequence lifetime of the first stars is then reduced, which eliminates the need for a top-heavy IMF. The "negative feedback" problem of the increasing metallicity is mitigated by effectively decoupling metal-enrichment from reionization in the QN picture, without recourse to a large formation rate of black holes. QNe also provide a local and prompt r-process enrichment for elements above $A \sim 130$, which can be related to the element abundance patterns in extremely metal-poor stars once chemical evolution studies are performed.

The properties of QN summarized above are the basis of our proposed modification of reionization and chemical enrichment wherein: (i) the most massive stars ($M \geq 40M_\odot$) in a conventional or slightly top-heavy IMF collapse to black-holes with a possible (small) contribution to reionization from accretion but no contribution to metallicity while (ii) the reionization is driven by intermediate-mass Pop III stars, whose higher mass members ($25M_\odot \leq M \leq 40M_\odot$) end up as QNe, providing the bulk of reionzing photons and enriching their environment in elements beyond $A \sim 130$, and (iii) low mass Pop III stars ($8M_\odot \leq M \leq 25M_\odot$) end up as type II SNe. A long-lived and metal-poor population of low-mass stars begins to emerge at the end of the reionization epoch (Greif et al. (2008)). In our scenario, the dying out of the first heavy stars coincides with a peak in the QN rate and therefore a peak in ionizing radiation.

In this paper, we first outline the basic observational constraints on reionization models (§2), followed by a description of QNe features in §3 (the explosion, the compact remnant and the ejecta), and then derive the properties of reionization by QNe (§4) as well as early r-process enrichment (§5). Our discussion and conclusions (§6) suggest observational tests of this scenario.

2. OBSERVATIONAL CONSTRAINTS ON REIONIZATION

We first examine the constraints provided by the Gunn-Peterson test and the latest WMAP results. Since even a tiny fraction of neutral H ($x_{\rm HI} \sim 10^{-3}$) in the IGM is sufficient to extinguish the transmitted flux bluewards of the Lyα emission line from distant Quasars, the onset of the Gunn-Peterson trough (Gunn & Peterson 1965) in recent observations of Quasar emission spectra (Schneider, Schmidt, & Gunn 1991; see Djorgovski et al 2001 and references therein) and the increased variance in the Gunn-Peterson optical depth at $z \sim 6$ shows that the IGM was transiting rapidly to a fully reionized state by then. This observation, although not a deep probe of reionization history, places a floor on the emissivity of UV photons required to keep up with recombination during the reionization epoch (Miralda-Escudé, Haehnet & Rees 2000):

$$\dot{N}_{\rm ioni.}(z) = 10^{51.2}\,{\rm s}^{-1}\,{\rm Mpc}^{-3}\ \left(\frac{C}{30}\right)\left(\frac{1+z}{6}\right)^3\left(\frac{\Omega_{\rm b}h^2}{0.02}\right)^2\ , \tag{1}$$

where $h = H_0/(100\ {\rm km\,s^{-1}\ Mpc^{-1}})$ is the scaled Hubble constant, and C is the clumping factor of the IGM related to small-scale ($\sim$ kpc) gas inhomogeneities caused by structure formation (Shapiro&Giroux 1987). We adopt a ΛCDM cosmology with $h = 0.72$, $\Omega_{\rm 0M} = 0.26$ and $\Omega_\Lambda = 0.74$, $\Omega_{\rm b}h^2 = 0.023$ which are consistent with the 5-year WMAP data (Dunkley et al. 2009).

The WMAP results provide important constraints on the Thompson optical depth at the time of reioinization. Cosmic Microwave Background (CMB) photons in the reionized epoch are Thomson rescattered by free electrons. This damps the primary temperature anisotropy of the CMB on scales smaller than the horizon size at rescattering, and generates additonal polarization on large scales (tens of degrees). The WMAP mission's measurements of the CMB polarization spectrum at low l have quantified this effect through an integrated Thomson optical depth τ_e. Recent analysis of 5-year WMAP data constrains it to be $\tau_e = 0.087 \pm 0.017$ for the best-fit ΛCDM cosmology (Dunkley et al. 2009); this is a much tightened value compared to the 3-year WMAP value $\tau_e = 0.089 \pm 0.030$ (Spergel et al. (2007)). These results rule out prompt reionization at redshift $z \simeq 6$ at 3.5σ and taken together with the varying Gunn-Peterson optical depth at $z \sim 6$, argue for an extended period of reionization stretching back to $z \sim 20$. The smaller mass fraction in collapsed halos at such high z (e.g. Iliev et al. 2007 and references therein) implies that a high emissivity of ionizing photon per unit mass is required early in the reionization epoch. This may be achieved with high formation efficiency of metal-free massive Pop III stars, but as we show in sections 3 and 4, our estimates for QN formation rates, the QN yield in heavy elements and UV photons imply that QNe allow for a more conventional star formation rate for Pop III stars as a viable alternative.

3. THE QUARK-NOVA

If a neutron star undergoes a deconfinement phase transition to quark matter in its interior, it can undergo core collapse, resulting in mass ejection of the outer crust (Takahara & Sato 1986; Gentile et al. 1993; Fryer & Woosley 1998;) and the formation of a stable strange quark star (a star made of up, down and strange quarks; e.g. Itoh 1970; Bodmer 1971; Witten 1984; Alcock et al. 1986, Bombaci et al. 2004). Ouyed et al. (2002) suggested that for sufficiently massive progeni-

tors, the deconfined cores physically separate from the overlaying hadronic layers giving rise to powerful novae. They termed this the Quark-Nova scenario (see also Keränen&Ouyed 2003).

As outlined in Keränen et al. 2005, the initial state for the QN is that of a deleptonized neutron star with a *(u,d)* core. In the quark-nova (QN) picture, the *(u,d)* quark core of a hybrid star that undergoes the phase transition to the *(u,d,s)* quark phase, shrinks in a spherically symmetric fashion to a stable, more compact strange matter configuration faster than the overlaying material (the neutron-rich hadronic envelope) can respond, leading to an effective core collapse. The two-step process, neutron to *(u,d)*, then *(u,d)* to *(u,d,s)* is crucial. In this scenario, the neutrinos come from weak reactions at the edge of the *(u,d)* core and can leak out easily into the surrounding cooler and deleptonized envelope where they can deposit energy. This is significantly different from phase conversion in a proto-neutron star stage where neutrino transport is slower (of the order of seconds) because of the hot and lepton-rich matter.

A complete dynamical treatment of the QN, including neutrino transport and full stellar evolution is only just beginning to be explored (Sagert et al. 2009) and preliminary results support a strong secondary explosion. However, we can make reliable estimates by adopting the viewpoint of numerous previous authors (Horvath & Benvenuto 1988; Lugones et al. 1994; Anand et al. 1997; Ouyed et al. 2002; Keränen et al. 2005; Jaikumar et al. 2007; Sagert et al. 2009) who assume a rapid adiabatic collapse on gravitational free-fall timescales ($\sim 10^{-4}$s) along with a conversion of the core to (u, d, s) quark matter on weak interaction timescales ($\sim 10^{-4}$s). The gravitational potential energy released in the collapse is converted partly into latent heat of the (presumably) first-order phase transition and partly into outward propagating shock waves from the supersonic motion of the (u, d, s) conversion front [5]. The temperature of the quark core thus formed rises quickly to (10-20) MeV since the collapse is adiabatic rather than isothermal (Gentile et al. 1993).

3.1. *The quark-nova compact remnant*

We assume that hot quark matter in the color-flavor-locked (CFL) phase is the true ground state of matter at high density. This is a superconducting phase that is energetically favored at extremely high densities and low temperatures (CFL; Alford et al. 1999). In this phase u, d, and s quarks pair, forming a quark condensate (a superfluid) that is antisymmetric in color and flavor indices. This state is reached by the QN compact remnant as it cools below a few tens of MeV (see Appendix A for a discussion on CFL and contamination of the universe).

Mannarelli et al. (2008) argue that CFL stars are unlikely to constitute a significant number of puslars since the r-mode is undamped for frequencies above 1Hz, due to the weak damping effect of mutual friction. However, this conclusion is derived for low temperatures $T \lesssim 0.01$MeV, while the temperature for the quark-nova is tens of MeV. As shown in Jaikumar et al. (2008), bulk viscosity from Kaons in the CFL phase is effective in damping out the r-mode at $T \geq 1$MeV, allowing the star to spin rapidly. Thus, the r-mode instability argument does not contradict the quark-nova mechanism (and the related CFL fireball; e.g. Vogt et al. 2004). However, it is clear that following the cooling phase of the quark-nova, the temperature will fall below 0.01 MeV. While mutual friction is too weak in this regime, other sources of viscosity may be important, such as shear viscosity from electromagnetic processes (it was shown in Manuel et al. (2005) that shear viscosity from phonons, though large, is inconsequential since it violates the basic hydrodynamic assumptions at such low temperatures). Therefore, we cannot comment on the ultimate fate of the CFL star below 0.01 MeV, but the quark-nova mechanism, which operates at much larger temperature, is not in obvious conflict with the r-mode instability.

3.2. *The quark-nova ejecta*

The gravitational potential energy released (plus latent heat of phase transition) during this event is converted partly into internal energy and partly into outward propagating shock waves which impart kinetic energy to the material that eventually forms the ejecta. Unlike Supernovae, neutrino-driven mass ejection in Quark-novae is not feasible, as neutrinos are trapped inside a hot and dense expanding quark core, once it grows to more than $\sim$2 km (Keränen et al. 2005). Mass ejection due to core bounce is also unlikely unless the quark core is very compact (1-2)km. A more promising alternative is mass ejection from an expanding thermal fireball that is a direct consequence of dense, hot quark matter in the color-flavor-locked (CFL) phase (Jaikumar et al. 2002; Vogt et al. 2004; Ouyed et al. 2005). Depending on the conversion efficiency of photon energy to kinetic energy of the ejecta, up to $10^{-2} M_{\odot}$ of neutron-rich material can be ejected at nearly relativistic speeds (Ouyed&Leahy 2009). Thus, QNe ejecta decompress material from the outer layers of exploding neutron stars. This is important for the operation of the r-process (Jaikumar et al. 2007).

3.3. *Dual-shock quark-novae*

If a QN occurs a few days to weeks (Yasutake et al. 2005; Staff et al. 2006) after the Supernova, the QN ejecta propagating into the Supernova envelope rapidly sweep up enough mass to become sub-relativistic. The collision of the two ejecta sets up a blast wave that propagates outward and re-energizes the Supernova ejecta. Part of the reshocked ejecta's energy is then radiated away in photons. This model for a "dual-shock" QN (hereafter dsQN) has been successfully applied to the observed light-curve of the most energetic Supernovae (eq. SN2006gy, SN2005ap, SN2005gj; see Leahy&Ouyed 2008). It is this radiation coming from the reshocked ejecta which we wish to evaluate as a potential reionizing source, keeping in mind that such dsQNe may be fairly frequent (discussed below).

4. QUARK-NOVAE AND REIONIZATION

4.1. *The Ionization Efficiency*

We estimate the frequency of dsQNe, denoted by $f_{\rm dsQN}$, by assuming a conventional IMF for massive stars

[5] More recent work, assuming realistic quark matter equations of state, argues for strong deflagration (Drago et al. 2007), but this too may be preceded by a compression shock (Lugones et al. 1994) in the hadronic phase.

(Scalo 1986), an average Galaxy density $n_g(z)$=$n_g(0)(1+z)^3$, and an average Type II supernova rate $f_{SN}(z)$ per year per Galaxy. For purpose of estimation, we take $(1+z) \sim 10$ as typical of the reionization epoch, $n_g(0)$=0.02/(Mpc)^3 and $f_{SN}(z) \sim 1$ yr^{-1} Galaxy^{-1}. We find $f_{\rm dsQN} = 0.1 x_{\rm QN} f_{SN} n_g(0)(10)^3 \sim 0.2$ yr^{-1} Mpc^{-3} where $x_{\rm QN} \sim 0.1$ is the fraction of stars in the 25-40$M_{\odot}$ range relative to all supernovae (8-40$M_{\odot}$) in the Scalo IMF. These stars are expected to undergo a Quark-Nova [6] with delay time between the supernova and the quark-nova decreasing with increasing mass (we assume conversion due to increased fall-back for more massive stars; see also Appendix B). The additional pre-factor of 0.1 is the fraction of quark-novae that can support an efficient dual shock. As argued in Leahy & Ouyed (2008), to be consistent with the fraction of superluminous supernovae such as SN2006gy, the fraction of quark-novae which happen fast enough for the dual shock to be effective is typically about 0.1. Galaxy mergers or a longer ionization history can easily increase $f_{\rm dsQN} \sim 10$ yr^{-1} Mpc^{-3}. We choose $f_{\rm dsQN} \sim 1$ yr^{-1} Mpc^{-3} as an average frequency of QN events during the reionization epoch.

To determine the number of ionizing photons, we note that the time-dependent luminosity of a dsQN is given by (Leahy&Ouyed 2008)

$$L_{\rm SN}(t) = c_{\rm v}\Delta T_{\rm core} n_{\rm ejec.} 4\pi R_{\rm phot.}(t)^2 \frac{dD(t)}{dt}\ , \quad (2)$$

where $c_{\rm v} \sim (3/2)k_{\rm B}$ is the specific heat of the ejecta, $\Delta T_{\rm core} \sim T_{\rm core}$ is the core temperature of the ejecta, $n_{\rm ejec}$ is the number density of the ejecta, $R_{\rm phot.}(t)$ is the photospheric radius and $D(t)$ is the photon diffusion length. This yields an integrated luminosity of 10^{51}ergs, in agreement with observations of SN2006gy, for the parameter choice $R_{\rm phot.}(t) \sim 3\times 10^{10}$km [7]. Furthermore, during time when the ejecta are optically thick (tens of days for the most energetic Supernovae), the luminosity can be approximated by $L_{\rm SN}(t)$=$\sigma 4\pi R_{\rm phot}(t)^2 T^4$ with $T \approx 10^4$K. This is close to the observed spectral peak of SN2006gy, in the first tens of days(Smith et al. (2007)). For metal-free Pop III progenitors however, we expect the peak to lie in the UV region ($T_{\rm pk} \approx (2-4)\times 10^4$K). The number of ionizing photons is then

$$N_{\rm ion} \approx \frac{N_0}{2.4}\int_{13.6/T_{\rm pk}({\rm eV})}^{\infty} \frac{dx\ x^2}{{\rm e}^x - 1} \quad (3)$$

where N_0=$0.244(4\pi\ R_{\rm phot}^3/3)T_{\rm pk}^3$ is the total number of radiated photons. We find N_0=2×10^{61}-2×10^{62} while $N_{\rm ion} \approx 3\times 10^{59}$-$4\times 10^{61}$ for the lower and upper limit of $T_{\rm pk}$ respectively. Since we have neglected the ionizing photon flux after the supernova ejecta becomes transparent, our estimate is a very conservative one. The exact number of ionizing photons is very sensitive to $T_{\rm pk}$ and $R_{\rm phot}(t)$, so we choose $R_{\rm phot}(t)$=3×10^{15}cm, $T_{\rm pk}$=3×10^4K, giving $N_{\rm ion}$=5×10^{60} as a reasonable estimate (see also Appendix C). Then, the corresponding emissivity of UV ionizing photons is conveniently expressed as

$$\dot{N}_{\rm ioni.,QNe} \approx 1.5\times 10^{53}\ {\rm s}^{-1}\ {\rm Mpc}^{-3} \times \left(\frac{f_{\rm dsQN}}{1\ {\rm yr}^{-1}\ {\rm Mpc}^{-3}}\right)\left(\frac{N_{\rm ion}}{5\times 10^{60}\ {\rm photons}}\right)\ . \quad (4)$$

which exceeds the floor on the emissivity of ionizing photons from Equation (1), even for the lower limit on $N_{\rm ion} \sim 3\times 10^{59}$.

It follows that the total number of ionizing photons *per baryon* produced in dsQNe during the epoch $\delta t_{\rm re}$ (between $z \sim 17$ and $z \sim 6$) is

$$f_{\rm re} \sim 2\left(\frac{N_{\rm ion}}{5\times 10^{60}}\right)\left(\frac{f_{\rm dsQN}}{1{\rm yr}^{-1}\ {\rm Mpc}^{-3}}\right) \times \left(\frac{\delta t_{\rm re}}{1\ {\rm Gyr}}\right)\left(\frac{R_{\rm uni.}}{1\ {\rm Gpc}}\right)^3\left(\frac{N_{\rm univ.}}{10^{79}}\right)^{-1}\ , \quad (5)$$

where $R_{\rm univ.} \sim 1$Gpc is the comoving radius of the universe at the reionization epoch ($(1+z) \sim 10$) and $N_{\rm univ.}$ is the total number of baryons of the universe, estimated to be $\sim 10^{79}$ baryons. Taking into account the uncertainties in Supernova rates in the distant past, we find from Equation (5) that QNe generate about 0.1-10 photons per baryon in the universe. A slightly higher (lower) $T_{\rm pk}$ or $R_{\rm phot}$ can substantially increase (decrease) this percentage. However, Equation (5) suggests the definite possibility that QNe can be an important source of reionizing photons.

4.2. *The Thomson Optical Depth*

The Thomson optical depth is the observational link with the ionization history of the universe. It is defined by the relation

$$\tau_e = \int n_e(z)\sigma_T c dt = \int f(z) n_{\rm H}(z)\sigma_T c \frac{dz}{(1+z)H(z)}\ , \quad (6)$$

where $n_e(z)$ is the co-moving electron density and $\sigma_T = 6.6524\times 10^{-25}$ cm^2 is the Thomson cross-section. In the second part of Equation (6), $f(z)$ is the hydrogen ionization fraction, n_H is the number density of Hydrogen, and $H(z)$=$H_0\left(\Omega_{0M}(1+z)^3+\Omega_\Lambda\right)^{1/2}$ is the Hubble parameter in terms of the cosmological redshift in a flat universe with a cosmological constant. We calculate $f(z)$ for QN, and then show how observational constraints on the optical depth provide constraints on QN associated with Pop III stars.

Each dsQN will set up an ionization front that propagates outward from $R_{\rm phot}(t)$. Detailed balance implies that the number of hydrogen atoms that are reionized $x(z)n_H(z)$ can be determined from (see §2.1 in Osterbrock 1988)

$$(1-x(z))\, n_{\rm H}\int_{13.6\ {\rm eV}}^{\infty} 4\pi j_\gamma \sigma_{\rm E} dE = x(z)^2 n_{\rm H}^2 \alpha(T)\ , \quad (7)$$

[6] Staff et al. (2006) estimated that 1 out of a 1000 neutron stars could undergo the deconfinement transition during a Hubble time from spin-down alone. Mass fallback is more efficient at rapid conversion and upto 1 in 10 neutron stars with progenitors above 25$M_{\odot}$ can become quark stars. Although this rate may seem high, Leahy & Ouyed (2007) have argued that this is consistent with the inferred birth rate of AXPs and SGRs (Gil&Heyl 2007), which are quark stars in their model.

[7] $R_{\rm phot.}(t)$=R_0+$v_{SN}t$ with R_0 being the radius of the progenitor star and v_{SN} being the speed of the shocked material.

where j_γ is the photon flux in units of cm^{-2} s^{-1} sr^{-1} erg^{-1}, $\alpha(T) = 4.18 \times 10^{-13}(T/10^4\ \mathrm{K})^{-0.726}$ cm^3 s^{-1} is the recombination coefficient (Mapelli & Ferrara (2005)) and $\sigma_{\rm E} \approx 6 \times 10^{-18}$ cm^{-2} is the photo-ionization cross-section of hydrogen atoms near threshold.

The flux j_γ can be related to $N_{\rm ion}$ at a particular distance from the QN. Since the thickness of the ionization boundary is much smaller than the Strömgren sphere, we can take the radius of the Strömgren sphere R_S as the typical distance at which Eq. (7) applies. Using a typical parameter set $R_S \approx 100$pc, $R_{\rm phot}(t)$=3×10^{15}cm and $T_{\rm pk}$=3×10^4K, we then obtain the solution for $x(z)$ from Eq. (7). To determine the volume fraction $f(z)$ of ionized hydrogen in the universe as a function of z, we use $f(z) \approx \nu(z)x(z)$ where the filling factor of non-overlapping Strömgren spheres from QNe, $\nu(z)$, is determined from (Barkana & Loeb (2001)

$$\frac{d\nu(z)}{dz} = \frac{0.1 x_{\rm QN} N_{I/B}}{0.76}\left(\frac{dF_{\rm col}(z)}{dz}\right) - \frac{\alpha(T) C n_{\rm H}^{(0)} \nu(z)}{a^3(1+z)H(z)} \tag{8}$$

In this equation, $N_{I/B}$ denotes the number of ionizing photons released in a QN per baryon in the star, $n_{\rm H}^{(0)}$ is the present-day density of neutral hydrogen and $a(t)$ is the scale factor defined such that $a(0) = 1$. The factor of 0.76 in the denominator is the primordial mass fraction of H (we adopt 0.24 for He; see §4.3). $F_{\rm col}(z)$ is the collapse fraction at high redshift which is estimated simply as the mass fraction in halos above the atomic cooling threshold in the Press-Schechter model (Press&Schechter 1974). An order of magnitude estimate, assuming 10^{57} baryons in a $1.4 M_\odot$ neutron star gives $N_{I/B} = 1000$ and yields $0.1x_{\rm QN}N_{I/B}$=10, which we keep fixed for all the curves in the figures below.

The most important factor in determining the ionization state is clumping factor C. We choose C=1,10,30 in displaying results in Fig. 1. These values are typical of the reionization era and are supported by more detailed modelling of the evolution of the inhomogeneities of the IGM (Furlanetto & Oh (2008a&b), Trac & Cen (2007), Miralda-Escudé et al. (2000)).

Our approximations also assume that a particular ionization front can be associated to a unique source, which is valid until the late stages of reionization when these fronts overlap. Since we do not include such effects, we simply set $\nu(z)$=1 when $\nu(z)$ crosses 1, leading to the artefact of discontinuities at low redshift in Fig. 1.

The vertical dashed line shows the observational lower limit on the reionization redshift (Fan et al. 2003) z=5.8. For $C \leq 10$ (moderate recombination rate), it is clear that QNe can make a large contribution to reionization.

We can now plot the results for the optical depth τ_e as a function of reionizing source turn-on at $z = z_0$ - shown in Fig. 2. These plots are determined from Eq. (6) for $C = 1, 10, 30$ with $f_{\rm re}$=10. The best-fit value for τ_e from ΛCDM cosmology (Dunkley et al. (2009)), assuming *prompt* reionization at $z = z_0$, along with 1σ limits are also shown.

The contribution of QNe to the optical depth depends sensitively on the clumping factor[8], but can be significant for $C \sim 10$, while for $C \sim 30$ or higher, the contribution is small. If $C \sim 1$, including QNe leads to too large an optical depth in comparison to the 5-year WMAP data. Other reionizing sources such as Pop III stars have been studied for consistency with the WMAP optical depth, with most reasonable models of their evolution suggesting a "shortfall" in the optical depth ($\tau_e \sim 0.05$) due to feedback effects that lead to self-regulation (Sokasian et al 2004), even in the case of high escape efficiency of the ionizing photons. Based on the results displayed in Figs.1 and 2, we suggest the intriguing possibility that QNe can help make up this shortfall.

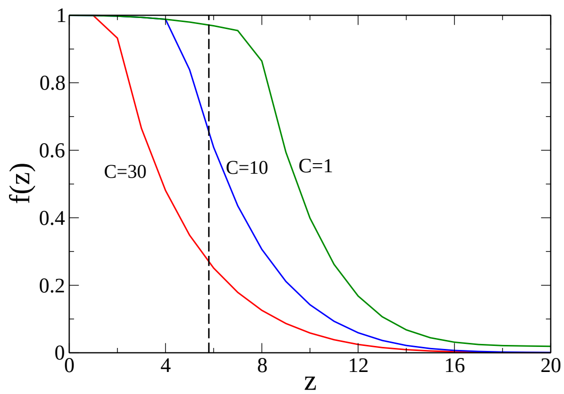

FIG. 1.— The fraction of ionized volume in the universe $f(z)$ from Quark-Nova events for various clumping factors C=1,10,30. The vertical dashed line denotes the observed lower limit of reionization at a redshift of $z = 5.8$.

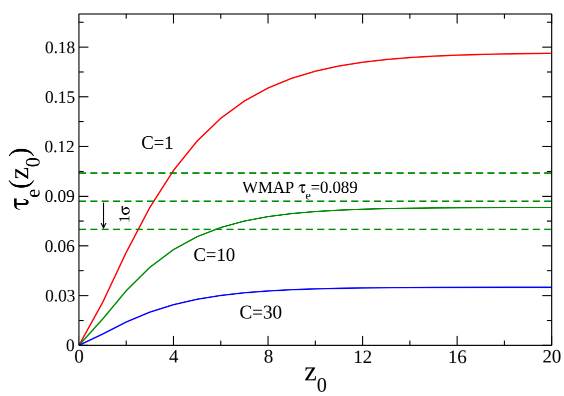

FIG. 2.— The Thompson optical depth $\tau_e(z)$ from eq. (6) for various clumping factors C=1,10,30.

4.3. *Helium reionization*

Helium reionization occured more recently, as suggested by a rapidly varying HeII optical depth at $z \approx 2.9$ with a small line of sight variation $\Delta z \approx 0.1$ (Reimers et al. 2005,2006). Observations of the HeII Lyα forest (Fardal et al. 1998) along lines of sight to bright quasars

[8] We have varied the clumping factor from 5-15 and find that correspondingly, τ_e varies from ≈ 0.13 to ≈ 0.066, assuming prompt reionization at $z \sim 20$. Thus, we do find sensitivity to the clumping factor, but this senstivity diminishes at large values of the clumping factor. A similar observation is made in relation to reionization simulations in inhomegeneous IGM (Miralda-Escudé, et al. 2000), where the effect of increasing overdensity saturates since late-time reionization (which is the era where the optical depth builds up) proceeds preferentially in underdense regions.

at $z \approx 3$ as well as empirical modelling of quasar luminosities and distributions (Furlanetto & Oh 2008a&b) hint that quasars are good candiates for HeII reionization. However, the latter work also cautions against a simple picture in which quasars are the only HeII ionizing source. This is because even a small fraction of HeII can absorb the redshifted Lyα photons, so that a modest contribution from a widespread low-intensity source above the HeII edge can also explain the apparent patchy nature of HeII reionization at $z \gtrsim 3$. Naturally, this raises the question: can QNe play a role in HeliumII reionization?

First, we consider the case for HeI, which has an ionization potential of 24.6eV. We find from Eq.(3) that only 5% of the photons that ionize HI can also ionize HeI; however there are far fewer HeI atoms $n_{\rm He}/n_{\rm H} \sim 0.08$. Since the recombination rates of HI and HeI differ only slightly, the ionization front for HeI may end up closely following that of HI. If we assume that Helium reionization does not affect HI reionization, then for $T_{\rm pk} = 3 \times 10^4$K, we find that the radius ratio of Strömgren spheres $R_S^{\rm HeII}/R_S^{\rm HII} \approx 1$.

In reality, the two ionization fronts are coupled since photons above 26.4eV can ionize both H and He. While we have not performed a detailed solution of the coupled fronts here, the results of such an exercise can be mocked up by a parameter $y = n_{\rm HI}a_\nu({\rm HI})/(n_{\rm HI}a_\nu({\rm HI}) + n_{\rm HeI}a_\nu({\rm HeI}))$ which is the fraction of photons with energy $E = h\nu \geq 24.6$eV that are used up to ionize Hydrogen (n is the number density and a_ν is the photoionization cross-section). Although a_ν is strongly energy dependent, the ratio $a_\nu({\rm HeI})/a_\nu({\rm HI})$ is about 8 for $h\nu \gtrsim 24.6$eV. With $n_{\rm HeI}/n_{\rm HI} \sim 0.08$, we find $y \sim 0.65$. This implies that $(1-y) \sim 0.35$ is the fraction of such photons that ionize Helium. The ratio of HII to HeII Stromgren radii depends on y as well as on the emissivity of the source (and recombination coefficients) and the ratio $R_S^{HeII}/R_S^{HII} \approx 0.35$ for $T_{\rm pk} \approx 3 \times 10^4$K. For a higher $T_{\rm pk} \approx 4 \times 10^4$K, this ratio is almost 1. It follows that the ratio of volume fractions $V_S^{HeII}/V_S^{HII} \approx 0.04$ for $T_{\rm pk} \approx 3 \times 10^4$K and ≈ 1 for $T_{\rm pk} \approx 4 \times 10^4$K. Including other smaller effects in Eq.(8) of our paper, such as the difference in recombination rates between H and He, and the number of ionizing photons/baryon for H and He, we find that the volume fraction of ionized Helium can vary dramatically from about 2% to 100% that of ionized Hydrogen. With such a strong dependence on the temperature of the ionizing source, it is not possible to make a robust claim on the efficacy of the Quark-nova on HeI reionization.

For HeII ionization, with a large ionization threshold of 54.6 eV, the emissivity of QNe implies that only about 1 in 10^5 photons can reionize HeII. Employing the front-decoupling approximation as for HeI ionization, we find that $R_S^{\rm HeIII}/R_S^{\rm HII} \approx 0.015$ and that even for the largest $T_{\rm pk}$=4×10^4K, approximately 5-10% of HeII is reionized by QNe by $z \sim 3$, depending on C [9]. Thus, we can conservatively say that QNe cannot be major sources of Helium reionization but they may constitute a low-intensity source compared to bright Quasars.

[9] This number will be lower once coupling between the HII, HeII and HeIII fronts is introduced

5. QUARK-NOVAE AND IGM ENRICHMENT

The large value of τ_e implies that the first stars appeared as early as $z \sim 20$, affecting the chemical evolution of the Galaxy and subsequent star-formation. A fingerprint of early chemical abundances has been preserved in the extremely metal-poor stars ([Fe/H] is used here as a proxy for the metallicity) such as HE-0107-5240 with [Fe/H]=-5.3 (Christlieb et al. 2004, Bessell et al. 2004) and CS 22949-037, with [Fe/H]=-4 (Depagne et al. 2002, Israelian et al. 2004) which constrains correlations between nucleosynthetic yields and the reionizing photon flux, since both are affected (the former somewhat weakly) by the star's metallicity. Previous works (Daigne et al. 2004; Tumlinson al. 2004) concluded that a top-heavy (40-100$M_\odot$) IMF with a lifetime of 50-100 Myr is required to simultaenously satisfy constraints set by the nucleosynthetic pattern in EMPs and early reionization. This requirement can change once the contribution of QNe to reionization is included. At present, we lack a comprehensive model of chemical evolution that takes into account the contribution from QNe. However, we can assess their importance in a global sense.

If most of the metals produced in supernovae explosions of the first stars are expelled into the IGM, Ricotti & Ostriker (2004) have estimated that the IGM metallicity is given by

$$Z_{\rm IGM} \sim (1 - f_{\rm BH}) 3g \times 10^{-3} Z_\odot \left(\frac{\tau_e}{0.1}\right) \tag{9}$$

where $f_{\rm BH}$ is the collapse-fraction of massive stars into black holes, $0.3 < g < 2$ depends weakly on the metallicity, and $Z_\odot$ is the solar metallicity. This assumes that the first stars are the sole reionizing sources, in which case, one needs to invoke a large black hole collapse fraction ~ 0.3 in order to satisfy the observational constraint on the metallicity of the early IGM $Z_{\rm IGM} \simeq 2 \times 10^{-4} Z_\odot$ (Schaye et al.(2003)). Such a large collapse fraction requires a top-heavy IMF.

QNe can change this scenario dramatically. As already shown, QNe can generate enough photons to provide a large optical depth, particularly if the clumping factor is small. Consistency with the optical depth then implies that the first stars contribute much less to the UV photon flux, so that τ_e from the first stars can be much less than 0.1. From Eq.(9), it is apparent that even with a small collapse fraction into black holes and a normal IMF, one may be able to satisfy the observational constraint on the IGM metallicity. It may not be necessary to invoke a large population of short-lived massive stars very early on and the IMF of Pop III stars could actually be more like the present-day IMF. We also note that since QNe only produce elements above $A \sim 130$, they essentially do not contribute to metallicity, which is associated with the production of much lighter elements such as C and O. Early IGM metallicity and reionization are decoupled in the QN scenario.

However, there is a link between early r-process abundance and reionization. The amount of r-process material ejected in a QN, as estimated from the energetics of the underlying phase transition, is about $10^{-4} M_\odot$. The frequency of such events during the reionization era is $f_{\rm dsQN} \sim .01$ yr^{-1} Galaxy^{-1}, so that the total r-process material ejected by $z \sim 6$ (10^9 yrs) is about $10^3 M_\odot$.

Since the total r-process abundance in our Galaxy at present is constrained to be $\sim 10^4 M_\odot$ (Wallerstein et al. (1997)), we conclude that about 10% of the total r-process elements at $A \gtrsim 130$ was produced early on in QNe, with the rest produced in Type-II supernovae or binary neutron star mergers, as QNe became much less frequent. In this way, QNe also provide a prompt and local initial enrichment of heavy elements $A \gtrsim 130$ that is seen in some of the oldest stars found to date. [10] We plan to study the implications for the observed scatter of r-process abundance in metal-poor stars in a subsequent study with a chemical evolution model.

6. CONCLUSIONS AND DISCUSSION

We have examined the role of Quark-Novae in reionizing the universe and contributing to its metal enrichment. In particular, we have suggested that:

(i) the most massive stars ($M \geq 40 M_\odot$) in a conventional or slightly top-heavy IMF collapse to black-holes with a possible (small) contribution to reionization from accretion but not to metallicity;

(ii) the reionization is driven by intermediate-mass Pop III stars, whose higher mass members ($25 M_\odot \leq M \leq 40 M_\odot$) end up as QNe, providing the bulk of reionzing photons and enriching their environment in elements beyond $A \sim 130$; and

(iii) low mass Pop III stars ($8 M_\odot \leq M \leq 25 M_\odot$) end up as type II SNe. A long-lived and metal-poor population of low-mass stars begins to emerge at the end of the reionization epoch (Greif et al. (2008)). In our scenario, the dying out of the first heavy stars coincides with a peak in the QN rate and therefore a peak in ionizing radiation.

Our calculations have shown that the photon flux produced in dual-shock Quark-Novae can be large enough to overcome recombination in the reionization epoch. Complete reionization by $z \sim 6$ is achieved if the clumping factor of matter is small $C \sim \mathcal{O}(1)$ but the optical depth is then $\tau_e \sim 0.17$, almost twice that of the latest WMAP measurement . We have made estimates for the evolution of the ionized fraction of the IGM in a simple model of non-overlapping outward-propagating ionization spheres. Our results imply that the optical depth from Thomson rescattering of CMB photons can be close to the value measured by WMAP, if the clumping factor $C \sim 10$. In this case, QNe provide about 60% of the reionizing photons. Alternatively, if $C \sim \mathcal{O}(30)$ or larger, QNe play a minor role in reionization compared to the first stars. QNe can be important for HI and HeI reionization, but their spectra do not contain sufficient high-energy photons to reionize HeII in any significant amount. Of central observational interest is the production of r-process elements beyond $A \sim 130$ in QNe, a feature which distinguishes QNe from SNe (the latter require larger entropy than predicted in current simulations to produce r-process elements beyond $A \sim 130$).

There are several novel aspects of the dsQN which must be addressed in future. The most important is the final composition of the Supernova ejecta from the first explosion which is subsequently shocked by r-process rich QN ejecta. This is a critical input to chemical evolution studies which can assess the effect of QNe on early r-process abundance patterns observed in metal-poor stars. In addition, the effect of QNe on the extra-galactic radiation field as well as its potentially large impact on the dissociation of molecular Hydrogen, which is a "negative feedback" to the formation of massive stars, remains to be analyzed. Further details relevant to the reionization era, such as the metallicity, the evolution of the clumping factor, the star formation efficiency in Galaxies, and the early supernovae rate will have some quantitative impact on our results. These quantities are poorly known at present and present a source of uncertainty in any model of reionization.

We close by predicting some important distinguishing features of QNe that are amenable to cosmological observations:

i) Quark-Novae and nucleosynthesis: QNe are a novel nucleosynthetic site for the *r*-process. We expect the QN ejecta to achieve γ-ray transparency sooner than Supernova ejecta since QN progenitors (i.e., neutron stars) lack extended atmospheres. Thus r-process-only nuclei with γ-decay lifetimes of the order of years (such as ^{137}Cs, ^{144}Ce, ^{155}Eu and ^{194}Os) can be used as tags for the QN (Jaikumar et al.(2007)), differentiating them from pair-instability SNe (due to the lack of any neutron excess) or core-collapse SNe (lower neutron excess than the QN ejecta). This could be observed by Gamma-ray satellites such as INTEGRAL.

ii) Quark-Novae and high redshift gamma-ray bursts: It has been argued that QNe provides an additional energy reservoir in the context of Gamma Ray Bursts (GRBs). The QN leads to a three stage model for long GRBs, involving a neutron star phase, followed by a Quark- Star (QS) phase and a plausible third stage that occurs when the QS accretes enough material to become a black hole. As shown in Ouyed et al. (2007) and Staff et al. (2007) by including the QS phase, one can account for both energy and extended duration of the prompt emission, X-ray flaring and the flattening observed in GRBs light curves. Our findings in this paper link QNe to the reionization epoch. The connection between QNe and GRBs suggested above would imply that GRBs should be observed as far back as the epoch of reionization.

To further pursue this connection between early QN and high redshift gamma ray sources, we note that the recent detection of GRB 080913 with *Swift* (Gehrels et al. 2004) at redshift 6.7 makes it the highest redshift GRB to date - more distant than the highest-redshift QSO (Fynbo et al. 2008). At $z = 6.7$ the burst occurred when the universe was less than a Gyr old when a high fraction of massive stars is expected to be of Pop III. It is thus possible that this GRB is a member of the long-soft GRBs produced by the collapse of the massive Pop III star (Greiner et al. 2009). However, making GRBs by the collapsar mechanism from Pop III has been questioned since simulations suggest that the exploding stars will retain its hydrogen and helium rich outer layers (e.g. Lawlor et al. 2008 and references therein). This violates the main requirement in the collapsar scenario that the star loses its extended envelope to enable the relativistic jet to punch through the compact core on timescale for long-soft GRBs (Fryer et al. 2001). Pop III binary

[10] The large ratios of [C/Fe],[O/Fe],[N/Fe] seen in the EMPs is believed to be related to lower mass stars, $20 < M/M_\odot < 40$ and would not be affected by QN events, which require heavier progenitors and only produce elements beyond $A \sim 130$.

evolution can both help remove the hydrogen envelope and spin up binary components. However, recent simulations question the efficiency in producing GRBs in this process (e.g. Belczynski et al. 2007 and references therein). Furthermore, classifying it as a long duration GRB begs the question, in the collapsar scenario, of how can a massive star produce a burst as short as 1 second? If instead GRB 080913 belongs to the short-hard class (Pal'shin et al. 2008; Xu 2008), then a neutron star-black hole merger is favored over a double neutron star merger, with the Blandford-Znajek process at play (Pérez-Ramírez et al. 2008).

The present detection rate of GRBs at $z > 5$ is about what is predicted on the basis of the star formation rate (Jakobsson et al. 2005). In addition, with hints of first stars having formed as early as $z > 20$ (Kogut et al. 2003), GRBs are believed to exist as early as $z \sim$ 15-20. The lack of many high-z GRBs can be explained in our model, as a consequence of clustering of GRB events near the end of the cosmic reionization era. We recall that in our model, the dying out of the first stars (at $z \sim$ 7-8 when adopting a normal IMF) coincides with a peak in the QN rate. This peak in the QNe rate (i.e. a peak in the GRB rate at $z \sim$ 7-8 in our model) offers a possible explanation for the sparsity of GRBs out to the highest redshifts ($z > 10$) despite the immense luminosity of both the prompt gamma-ray emission and X-ray and optical afterglows of GRBs, and the current technology (i.e. the high detection rate delivered by *Swift*). While a merger origin of GRB080913 cannot be definitively ruled out, we suggest that this burst could instead be the first ever detection of a QN near the end of the cosmic reionization era.

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APPENDIX

A: POLLUTION BY CFL STRANGELETS

By assuming that strange quark matter is absolutely stable, the universe might be polluted by strangelets (e.g. ejected during coalescence of quark stars in binary systems; e.g. Madsen 2005). With a NS-NS binary collision rate of $10^{-4} - 10^{-6}\mathrm{yr}^{-1}\mathrm{Galaxy}^{-1}$ (Belczynski et al., 2002), we expect the rate of QS-NS collisions to be at most $10^{-5} - 10^{-7}\mathrm{yr}^{-1}\mathrm{Galaxy}^{-1}$. This will be somewhat reduced by the fact that, just as about 50% of binary systems are disrupted by a supernova, binary neutron stars can become gravitationally unbound in a quark-nova. The amount of ejected mass will also be smaller since quark matter is stiffer than neutron matter. Following Madsen (2005), we have estimated the flux of CFL strangelets in the Earth's vicinity, accounting for factors such as the geomagnetic cutoff on the rigidity of the strangelet, and the confinement time of typical CFL strangelets in our Galaxy. We find this flux (assuming strangelet number distribution to peak in the baryon number range $A \sim 10^2 - 10^3$) to be $\sim 10^2 - 10^4\mathrm{m}^{-2}\mathrm{yr}^{-1}\mathrm{sr}^{-1}$. This flux is too low to be tested conclusively by terrestrial experiments (although for particular values of the strangelet charge, 1 or 2 candidate events have been identified; see Finch 2006). The satellite-based AMS-02 detector launched recently has a threshold senstivity that is sufficient to detect the expected flux of CFL strangelets from quark star collisions across a wide range in A; these results are expected within a few years. Lunar searches, which benefit from lack of geological mixing and no magnetic field deflection, are also just approaching the required flux senstivity. Thus, at present, the strange quark matter hypothesis is not inconsistent with observations, even taking into account the binary QS-NS collisions and consequent pollution by CFL strangelets. The most recent work about strange star binary mergers by Bauswein et. al. (2008) found that for high values of the MIT bag constant, strange stars could co-exist with ordinary neutron stars as they are not converted by the capture of cosmic ray strangelets. Combining their simulations with recent estimates of stellar binary populations, Bauswein et al. (2008) conclude that an unambiguous detection of an ordinary neutron star would not rule out the strange matter hypothesis.

B: QUARK-NOVAE PROGENITORS

The fit to the observed light curve of SN2006gy, Leahy & Ouyed (2008) assumes QNe progenitor mass in the (40-60)$M_\odot$ range. However, one can employ the parameter degeneracy in that fit to examine the dual-shock scenario with the more conservative mass range of (25-40)$M_\odot$ which is more in line with the literature (e.g. Heger et al. ApJ 591 2003; Nakazato et al. 2008) which suggets prompt BH formation above $40M_\odot$. It should be noted however that the effect of the fireball in the CFL phase (Ouyed et al. 2005) has not been taken into account in any of these simulations, which means the range 25-40$M_\odot$ could be somewhat underestimated.

C: SHOCK EFFICIENCY IN DUAL-SHOCK QUARK-NOVAE

According to Ouyed et al. (2007), the shock efficiency varies as $\rho^2_{\mathrm{env.}}$ with the mean SN envelope density given by $\rho_{\mathrm{env}} \propto M_{\mathrm{env.}}/R^3_{\mathrm{env}}$. If we choose $40M_\odot$ instead of $60M_\odot$ for the progenitor of the SN, and demand the same efficiency, we find that the collision radius should be $R_{40} = (40/60)^{1/3} \times R_{60} \sim 0.876 \times R_{60}$ and the delay time $t_{\mathrm{delay},40} = 0.876 t_{\mathrm{delay},60} \sim 0.876 \times 15$ days ~ 13 days. Similarly, $T_{\mathrm{pk},40} = (R_{40}/R_{60})^{1/2} T_{\mathrm{pk},60} = (0.876)^{1/2} T_{\mathrm{pk},60} \sim 0.94 T_{\mathrm{pk},60}$.

With these changes, we find a reduction factor of 0.6 in the total number of ionizing photons. This does not change our order of magnitude arguments on the ionization efficiency and we had in any case adopted a very conservative estimate for the number of ionizing photons initially by neglecting photons emitted after the ejecta becomes transparent.

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